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Characterization of the Fracture Morphology of Commercially Pure (cp)-Titanium Micro Specimens Tested by Tension-Compression Fatigue Tests

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Abstract

Surface modification could improve functional or mechanical properties of components, which are used for example in biotechnological or automotive applications. Thereby, small structures produced by micro milling or laser structuring processes are in the same order as the grain size. They act as geometrical notches and could reduce the mechanical properties.

In this work we will show detailed investigations of the fracture morphology of tension-compression tested micro notched specimens. The fracture surfaces were analyzed with a Scanning Electron Microscope (SEM) to determine the location of the failure. Furthermore metallographic microsections of some specimens were prepared to analyze the crack growth in detail: the aim is to investigate whether the crack propagation is affected by metallurgical features, such as the crystallographic orientation of the grains or microstructural barriers like grain boundaries. With these analyses we expect to be able to correlate the different stages of crack growth.

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1. Introduction

To achieve high performance components the surface of engineering parts is coming more and more into the focus of research. To reach good functionality and suitable mechanical properties different manufacturing processes for the surface modification are possible, for instance micro milling [1] or laser structuring [2]. These processes introduce very small notches, whose in dimensions which vary from smaller than the grain size up to a depth of a few grains, into the component surfaces. Normally, notches reduce the fatigue limit of components due to stress concentrations.

The question is whether these small notches influence the mechanical properties and in particular the endurance limit. In a previous work tension-compression fatigue tests were done with laser structured, micro milled and unstructured cp-titanium specimens [3]. The results do show an influence of the micro notches on the endurance limit, depending on the dimension of the notches in relation to the grain size. The laser structured specimens with deeper notches failed directly at the notch root and showed typical cleavage planes at the crack initiation area. The crack initiation of the other specimens occurred by slipping processes. The reason for the different fracture morphologies is not completely understood yet. One reason could be a strengthening at the melted zone of the laser structured notch. Another reason could be the existence of a local stress concentration at the notch, which increased the susceptibility of cp-titanium for cleavage fracture [4].

The notches in our investigated specimens act similarly as microstructural small cracks. The initiation of the crack is controlled by the stress concentration at the notch root. Furthermore, the crack propagation depends on local microstructural features like grain size, structure of the grain boundaries, and the crystallographic orientation of the neighboring grains [5-7]. The question is whether a crack can be initiated and then grows and cause failure of the specimen, or whether the cracks will be constrained by the microstructural barriers, e.g. grain boundaries. The present work investigates this problem by analyzing the fracture surfaces of micro structured specimens with a SEM and by light microscope analyzes of metallographic microsections.

2. Material and Methods

2.1. Material and chemical composition

The tested material is a commercially pure (cp)-titanium (grade 2) with the chemical composition as shown in Table 1. The average grain size is approximately 30 μm .

Table 1. Chemical composition of cp-titanium (grade 2)

wt-%	N	C	H	Fe	O	Ti
analysis	0.004	0.042	0.003	0.037	0.127	balance
max. ASTM B265	0.05	0.60	0.013	0.20	0.18	balance

2.2. Specimen geometry and surface states

The geometry of the microspecimens, which were analyzed by tension-compression fatigue tests, is shown in Fig. 1. The specimens were cut out of sheets. The thickness of the specimens depends on the machining process and lies between 0.5 and 0.6 mm. Four different surface states were produced and tested: two of them were laser structured at only one side, and the other two were faced milled and micro milled at both sides. Fig. 2 shows the longitudinal metallographic microsections with the notch geometry after the different machining processes. For comparison an untreated technical surface state and a both-side faced milled surface state were tested, too.

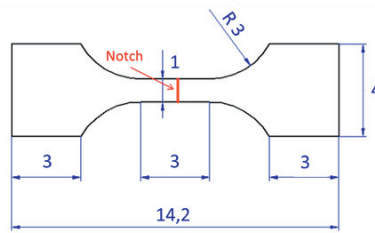


Fig.1. Geometry of the microspecimen (values in mm).

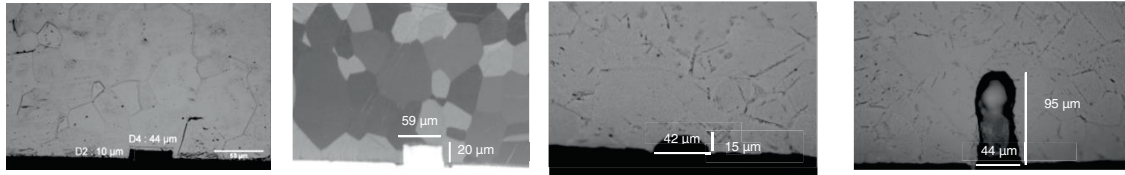


Fig.2. Notch geometry for (a) micro milled notch 10 μm depth; (b) micro milled notch 20 μm depth; (c) laser structured notch "L1" 15 μm depth; (d) laser structured notch "L2" 95 μm depth

2.3. Fatigue Tests and metallographic preparation

The edges of the specimens were mechanically polished before testing. The tension-compression fatigue tests were realized with an electro dynamic testing machine (Bose® ElectroForce 3230). The stress controlled tests were performed with sinusoidal loading at a frequency of 50 Hz with a load ratio of $R = -1$ at different stress amplitudes. The ultimate number of cycles was 10^7 .

The failed specimens were analyzed with a scanning electron microscope. Some specimens, which showed representative or special features in the fracture surface, were chosen for further metallographic investigations. Therefor the broken specimens were embedded in an epoxy resin, grinded, and polished so that the microsection for light microscope observation was perpendicular to the fracture surface. The section planes are marked by dotted lines in Fig.4-7. The last polishing step was combined with intermediate etching with a 5 % HF-solution. The microsections were analyzed in the optical microscope under polarized light.

3. Results

3.1. Fatigue tests

The results of the tension-compression fatigue tests are shown in Fig. 3. It is obvious that the fatigue strength decreases with increasing notch depth. But the influence on the endurance limit is less distinct for the notches which are in the same scale as the grain size. The specimens which were chosen for further metallographic investigations in the scope of this work are marked in the curve.

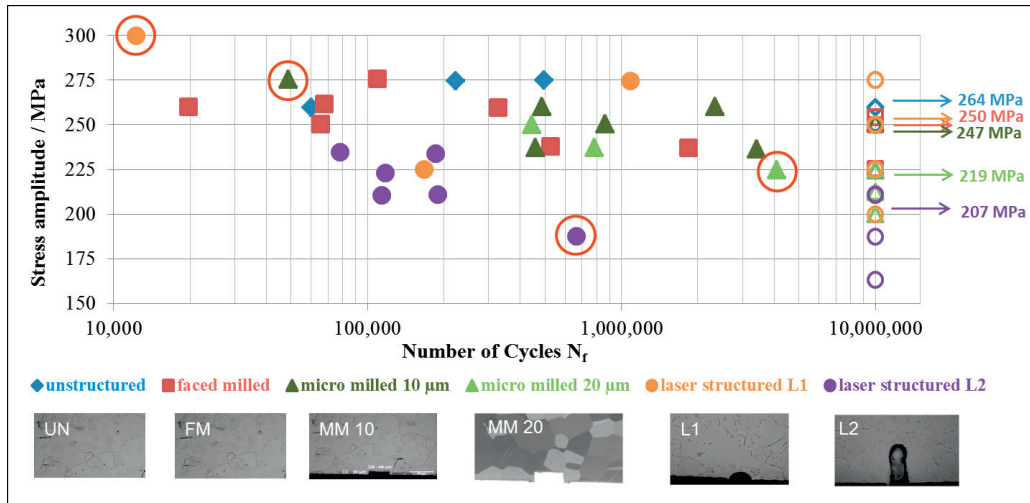


Fig.3. S/N diagram of tension-compression fatigue tests ($R=-1$)

3.2. Fractography

Fig.4a shows the fracture surface of the laser structured specimen L1 (specimen A). There are two crack initiation sites, which are marked in the picture with white arrows. All broken specimens of the laser structured L1 type did not fail at the notches but at the radius transition between gauge length and grip area. This implies that the notch geometry L1 has no influence on the crack initiation and finally on the endurance limit. This conclusion can also be drawn from the form of the S/N curve. The endurance limit of the L1-state is in the same order as that of the unstructured specimens. The cracks initiated by sliding processes over one or two grains, followed by transgranular crack propagation over a few grains. The residual fracture happens with large plastical deformations, which are observable by the typical comb structure in the SEM-image and also through the deformed grains in the optical microscope-image.

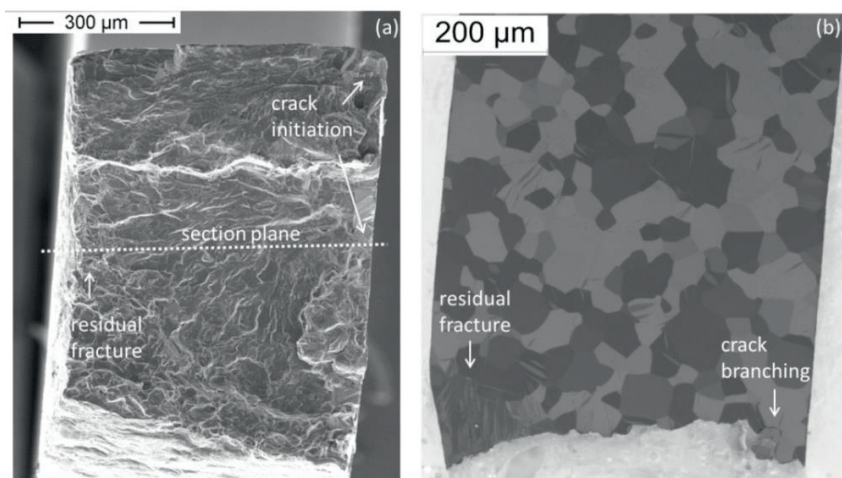


Fig.4. Fracture surface (a) and microsection (b) of specimen A (laser structured L1)

The fracture surface and the crack path of the laser structured specimen L2 (specimen B) are shown in Fig. 5. In contrast to the L1-specimens, all L2-specimens showed the crack initiation at the notches. Each laser notch root

constitutes a crack initiation site. The cracks were initiated by a cleavage process. The crack propagation is influenced by the orientation of the grains. In the light microscope-image in Fig. 5b a few crack branching points are visible. The propagation occurs trans- and intergranular. Some cracks are stopped by grain boundaries. This behavior is typical for the crack propagation stage I [8]. The further propagation (crack stage II) is transgranular. The residual fracture area is again characterized by plastic deformation but limited to only two up to three grains.

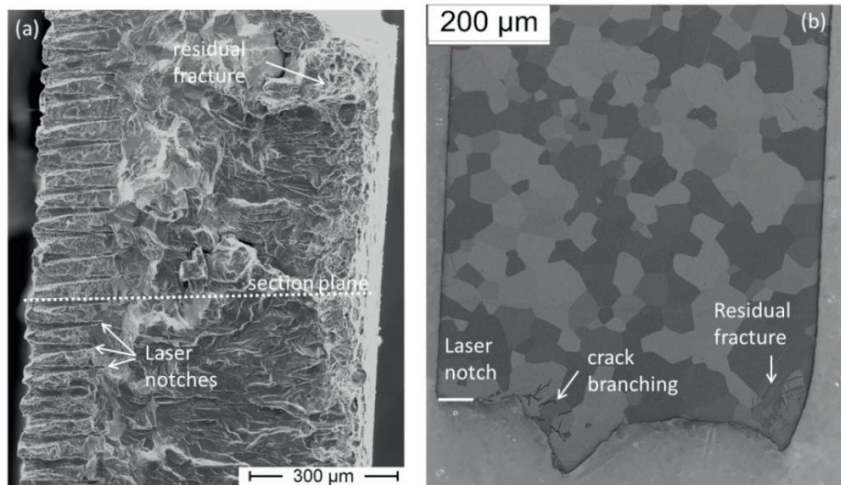


Fig.5. Fracture Surface (a) and microsection (b) of specimen B (laser structured L2)

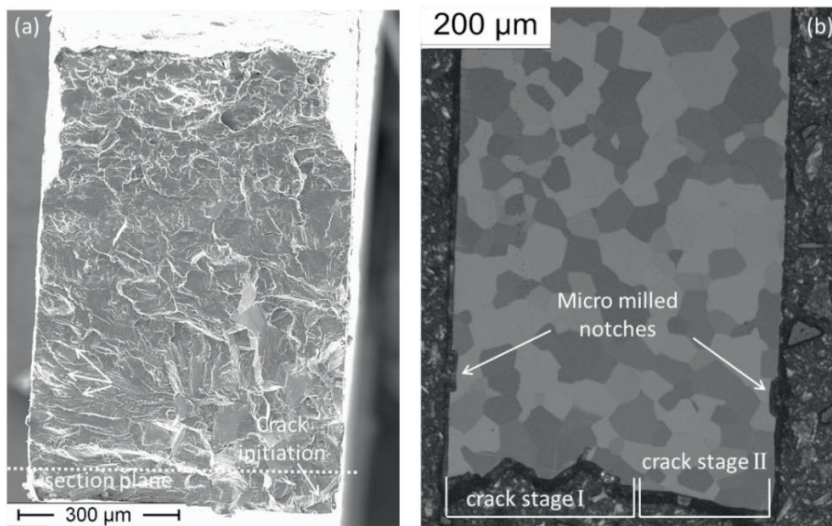


Fig.6. Fracture Surface (a) and microsection (b) of specimen C (micro milled 10 μm)

Fig.6 illustrates the SEM- and light microscope-images of the micro milled specimen with a notch depth of 10 μm (specimen C). The crack did not initiate directly at the notch root, but in a grain near the milled structure so that the notch geometry is visible in Fig.6b. As the section plane does not intersect the residual fracture area, there is no plastic deformation area visible in the microsection. The crack propagation in stage I is predominantly transgranular, and the stage II propagation is transgranular.

The fracture surface and microsection of the micro milled specimen with the 20 μm deep notch are shown in Fig.7. The crack initiated at one edge of the rectangular notch. The crack changed its propagation plane, so that the opposite notch the is not visible in microsection.

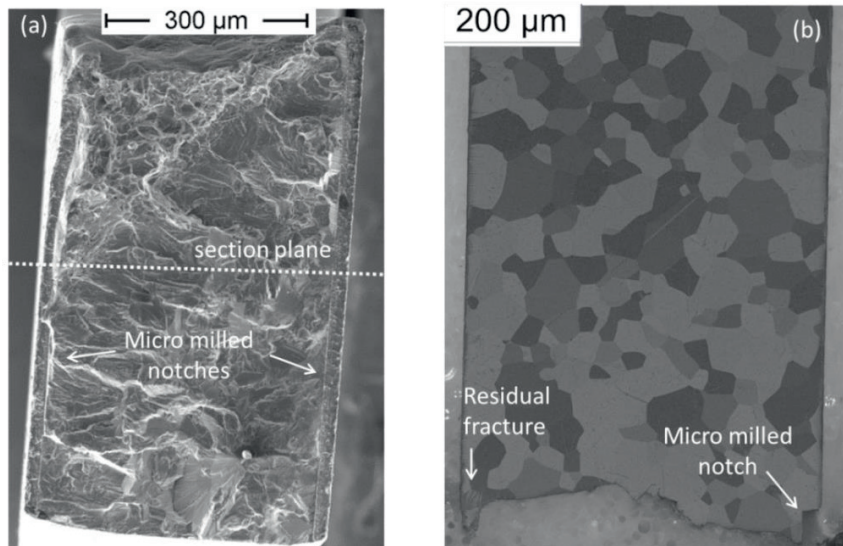


Fig.7. Fracture Surface (a) and microsection (b) of specimen D (micro milled 20 μm)

4. Summary

This work presents investigations of the fracture morphology of cp-titanium-microspecimens with different structuring states. The endurance limit is affected by the notch geometry in relation to the grain size. Notches which are larger than the microstructural dimensions result in a decreased fatigue limit. Notches which are smaller than approximately 15 μm do not significantly influence the fatigue limit.

All specimens show a microstructure dependent propagation behavior in crack stage I, where the cracks search the best way through and along the grains and are partially stopped by grain boundaries. Crack stage II is characterized by a straight transgranular crack propagation and the residual fracture by high plastic deformations. Since only the laser structured L2-specimens show cleavage planes at the crack initiation area, it is likely that increased stress concentration at the notch roots is responsible for their existence.

The optical light microscope investigations of the microsections permit a good correlation to the SEM-investigations. The crack path can be reproduced in that way.

Acknowledgements

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